Pressure effect on high-T_c superconductors and Casimir Effect in nanometer scale

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(Dated: July 5, 2008)

Abstract

Considering CuO_2 conducting layers present in high Tc superconductors as plasma sheets, we proposed a prescription for the T_c pressure behavior taken into account the Casimir effect. The Casimir energy arises from these parallel plasma sheets (Cu-O planes) when it take placed in the regime of nanometer scale (small d distance). The charge reservoir layer supplies carries to the conducting $nCuO_2$ layers, which are a source of superconductivity. The pressure induced charge transfer model (PICTM) makes use of an intrinsic term, which description is still unclear. Considering Casimir energy describing the T_c for the case of hight-T_c superconductors, we propose an explicit expression to the intrinsic term. Realistic parameters used in the proposed expression have shown an agreement with experimental intrinsic term data observed in some high-T_c compounds.

PACS numbers: 74.72.Jt,74.25.Dw,74.62.-c,74.25.Fy

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I. INTRODUCTION

The high Tc cuprates superconductors have been described since its discovery in 1986 [1] as composed by two major constituents in their unit cell; MBa_2O_{4-d} as a charge reservoir block (M=Cu,Tl,Hg,Bi,C) and a conducting $nCuO_2$ layers (n=2,3,4,5,6). The charge reservoir layer supplies carries to the conducting $nCuO2$ layers and these carriers in CuO_2 planes are a source of superconductivity.

In 1993, Putilin *et al.* [2] have obtained a new family $HgBa_2Ca_{n-1}Cu_nO_y$ (n=1,2,3 ...), which has presented the highest T_c (134K) for n=3. This Hg-cuprate system loss its superconducting properties due to CO_2 contamination, however this matter has been overcome by partial substitution of mercury (Hg) by rhenium (Re) [3, 4]. Taken into account the rhenium (Re) substitution, its was possible for other research groups to study the physical properties of this family without problems like sample degradation and with a precise oxygen content control.

Our group has investigated the $Hg_{0.8}Re_{0.2}Ba_2Ca_2Cu_3O_{8+\delta}$ in the ceramic form (polycristaline) since 1998 [5, 6]. This compound can be described as three CuO_2 conducting planes separated by layers of essentially insulating material, which is a feature that high Tc cuprates have in common.

The mercury family $HgBa_2Ca_{n-1}Cu_nO_y$ (n=1,2,3 ...) has a number of CuO_2 conducting layers proportional to n. Taken into account the existence of these $nCuO_2$ conducting layers in cuprate superconductors, in 2003 it was indicated [7] that Casimir effect [8] should occur between the parallel superconducting layers in high Tc superconductors. For ideal conductors layers separated by vacuum the Casimir energy is described as:

$$E_c(d) = -\frac{\pi^2 \hbar c A}{720 d^3} \tag{1}$$

where A is the plate's area, and is larger as compared with the distance d. This equation describes the Casimir energy for two parallel plasma sheets with larger separation d.

Our previous study about $Hg_{0.8}Re_{0.2}Ba_2Ca_2Cu_3O_{8+\delta}$ [9], with optimally oxygen content ($\delta = 8.79$ and $T_c^{max} = 133K$), has indicated dT_c/dP=1.9(2)$KGPa^{-1}$. Considering that the optimally oxygen content represent the optimally condition for carrier transport in the Cu-O cluster formed by $3-CuO_2$ layers, we attributed the T_c increment with external pressure as a reduction of the d distance between the Cu-O clusters. In this scenario we propose a investigation of the nanometric distances correlation between Cu-O clusters and T_c variation in the frame of Casimir energy.

II.   CASIMIR EFFECT IN HIGH-T_c SUPERCONDUCTORS

In high-T_c superconductors the hole of the Casimir plates can be attributed to the $nCuO_2$ layers, which form a Cu-O non-superconducting charge carriers layers initially, and are able to form the superconductors layers below T_c. As these superconducting Cu-O cluster of layers are separated by two orders of magnitude smaller than the London penetration depth, the Casimir effect is reduced by several orders of magnitude. Taken into account a small d (nanometric scale), Bordag [10] has proposed for a Transverse Magnetic (TM) mode, a modification on Casimir energy, as following:

$$E_c(a) = -5.10^{-3}\hbar c A d^{-5/2}\sqrt{\frac{nq^2}{2mc^2\epsilon_0}} \qquad (2)$$

In the equation (2) A is the sheet area, d is a nanometric distance between the sheets, and n represents the carrier density.

In the regime of small distances (nanometric scale) between the clusters of Cu-O layers, the Casimir effect becomes a van der Waals type effect dominated by contributions from TM surface plasmons propagating along the ab planes [7]. Within the Kempf model, the superconducting condensation energy is the same order of magnitude as the Casimir energy. Taken into account the density of states in the case of a Fermi gas in two dimensions, the transition temperature T_c was predicted [7, 11] as below:

$$T_c = \frac{2^{3/4}\pi^{1/2}\hbar^{3/2}e^{1/2}n^{1/4}}{10\eta k_B m^{3/4}\epsilon_0^{1/4}d^{5/4}} \qquad (3)$$

The equation (3) presents $m = 2*\alpha*m_e$ as a carrier effective mass, n as a carrier CuO_2 layer density, $\eta = 1.76$ BSC parameter, d as a distance between two $nCuO_2$ clusters of layers, ϵ_0 as vacuum electrical permeability.

Our interpretation is that α in $m = 2*\alpha*m_e$ represents a factor associated with effective mass of the conducting superconductor carrier, which came from the convolution of local symmetry of CuO_2 (Ex. Octahedral, pyramidal or plane) with the crystal symmetry. The main relation pointed out by the equation (3) is that T_c is a function of $\alpha^{3/4}$, $n^{1/4}$, and $d^{-5/4}$. In order to verify the equation (3), it was built the Table I using realistic values found in our laboratory and in the literature [9, 16, 17, 18, 19, 20, 21, 22, 23].

III.   PRESSURE EFFECT ON HIGH-T_c

As a high-T_c superconductor probe, it was investigated the effect of hydrostatic pressure under $Hg_{0.82}Re_{0.18}Ba_2Ca_2Cu_3O_{8+\delta}$, labeled here as (Hg,Re)-1223. First of all, to describe the effect of hydrostatic pressure, it was assumed that the volume compressibility of (Hg,Re)-1223 is the same one determined for $Hg_1Ba_2Ca_2Cu_3O_{8+\delta}$ compound (labeled as Hg-1223), which is close to 1%/GPa [12]. For (Hg,Re)-1223, when the hydrostatic pressure is closer

to 0.9GPa, the crystal unitary cell volume is reduced down to -0.8%. The variation of hydrostatic pressure up to 1.2 GPa on (Hg,Re)-1223, with different δ causes different T_c changes [9]. The reduction of the unitary cell, under hydrostatic pressure, leads to an variation of T_c and it is associated to contraction of the *a, b and c*-axis. The different T_c dependence, concerning external hydrostatic pressure, may be interpreted by the pressure induced charge transfer model (PICTM) modified by Almasan et al. [13]. The variation on T_c can be described by Neumeier and Zimmermann [14] equation:

$$\frac{dT_c}{dP} = \frac{\partial T_c^i}{\partial P} + \frac{\partial T_c}{\partial n}\frac{\partial n}{\partial P} \tag{4}$$

where the first term is an intrinsic variation of T_c with pressure and the second is related to changes in T_c due to variation on the carrier concentration in $nCuO_2$ conducting layers, which are caused by the pressure's change. For the case of external hydrostatic pressure effects on samples with optimally oxygen content, such as $Hg_{0.8}Re_{0.2}Ba_2Ca_2Cu_3O_{8+\delta}$ with($\delta = 8.79$), the second term in equation (4) vanish. Then, under this condition we have:

$$\frac{dT_c}{dP} = \frac{\partial T_c^i}{\partial P} \tag{5}$$

So, for this case, the T_c variation will be determined only by the intrinsic term. The non-negligible intrinsic term $\partial T_c^i/\partial P$ suggests an effective contribution of the lattice to the mechanism of high-T_c superconductivity against the role of carriers. The $Hg_{0.8}Re_{0.2}Ba_2Ca_2Cu_3O_{8.79}$ has shown $\partial T_c^i/\partial P = 1.9K/GPa$ [9] and the YBa_2Cu_3O7 compound has presented $\partial T_c^i/\partial P = 0.9K/GPa$ [14].

The intrinsic term has been presented with a physical meaning, but without an exact description since its introduction in 1992 [13]. However, if the T_c can be associated to the temperature from Casimir energy, as proposed by equation (3), the equation (4) can be rewriting as following:

$$\frac{dT_c}{dP} = \frac{\partial T_c}{\partial d}\frac{\partial d}{\partial P} + \frac{\partial T_c}{\partial \alpha}\frac{\partial \alpha}{\partial P} + \frac{\partial T_c}{\partial n}\frac{\partial n}{\partial P} \tag{6}$$

For samples with optimally oxygen content the third term is vanish, as justified before. For this optimally conditions there is a direct correspondence between the intrinsic (5) term and the other two significant terms (6), as specified below:

$$\frac{\partial T_c^i}{\partial d} = \frac{\partial T_c}{\partial d}\frac{\partial d}{\partial P} + \frac{\partial T_c}{\partial \alpha}\frac{\partial \alpha}{\partial P} \tag{7}$$

Substituting the equation (3) in (7) we have an explicit expression to the intrinsic term, as following:

$$\frac{\partial T_c^i}{\partial d} = \frac{-5}{4}T_c\frac{1}{d}\frac{\partial d}{\partial P} + \frac{-3}{4}T_c\frac{1}{\alpha}\frac{\partial \alpha}{\partial P} \tag{8}$$

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IV. DISCUSSION

The signal of both terms in the equation (8) are negative, however the intrinsic term is positive, when the pressure is increase. This behavior can be justified by the negative signal of the both derivative terms,

$$\frac{\partial d}{\partial P}, \frac{\partial \alpha}{\partial P} \to (P \uparrow) \to \frac{\partial d}{\partial P} < 0, and \frac{\partial \alpha}{\partial P} < 0 \tag{9}$$

The first derivative term represents the compression coefficient in c axis direction. The crystallography c axis is associated with the nanometric distance d between the two $nCuO_2$ clusters of layers, located each one in different adjacent crystals cells. As consequence one can write the following expression:

$$K_c = -\frac{1}{c}\frac{\partial c}{\partial P} = -\frac{1}{d}\frac{\partial d}{\partial P} \tag{10}$$

The second derivative term in (9) represents a variation of the effective carrier mass, which came from the change on the dispersion relation under pressure. X-ray diffraction and XANES analysis of the (Hg,Re)-1223, with optimally oxygen content has indicated a tendency of O-Cu-O bond angle being closest 180° [15]. The effect of increase the external pressure is to change this O-Cu-O bond angle to 180°. In our point of view, α coefficient is related with the convolution of CuO_2 local symmetry and crystal symmetry. As consequence, α value is reduced as comparing with the initial value (ambient pressure), when the pressure is increase.

$$(P \uparrow) \to \frac{\partial \alpha}{\partial P} < 0 \tag{11}$$

Therefore, the final signal of $\partial T_c^i / \partial P$ is positive, and the intrinsic term will present a positive behavior under external pressure.

In order to verify the agreement of the equation (8), it was built the Table II using realistic values found in the literature [12, 16, 17, 18, 19, 22, 23] and in our laboratory for compounds with $nCuO_2$ superconducting layers. Moreover, the recent discovery (April 2008) of a new superconductor family by Takahashi *et al.* [20] with ($FeAs$) superconducting layers suggested that we included the $SmOFeAs$ [21] compound in the Table II also.

The values reduction of effective mass coefficient α suggested a relation with the total symmetry (local CuO_2 + crystal) configuration. Computing simulation are going on in order to verify the variation of dispersion relation in the reciprocal space in order to compare the values suggested in the Table II.

V. CONCLUSION

The Casimir energy was related with the superconducting condensation energy [7, 11], taken into account the density of states in the case of a Fermi gas in two dimensions. As con-

sequence, the transition temperature T_c was predicted as function of $m^{3/4}$, $n^{1/4}$, and $d^{-5/4}$. Within this scenario, the α coefficient in $m = 2 * \alpha * m_e$ was interpreted as the effective carrier mass factor from the dispersion relation, taken into account the convolution between local symmetry of CuO_2 (Ex. Octahedral, pyramidal or plane) and the crystal symmetry. The values found by T_c expression is in agreement with the experimental T_c values found in the principal superconductors described in the literature and (Hg,Re)-1223 measured in our laboratory. The T_c's behavior under external hydrostatic pressure (described by PICTM) shows an intrinsic term, which is identified here with the variation of Casimir energy. This intrinsic term's pressure dependence presents an explicit expression proportional to the compressibility coefficient of c axis and the effective mass of carrier charge. For the best of our knowledge, the $\partial T_c^i / \partial P$ has not presented an explicit expression before. Our propose describe the dependence of intrinsic term with pressure in agreement with the values found in the literature.

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VI. LIST OF TABLES

TABLE I: Critical temperature evaluated by Casimir energy T_c^{Cas}, T_c^{ref} obtained in the references, and correlations

Compound	d(nm)	n(m^{-2})	α	T_c^{Cas}(K)	T_c^{ref}	Cu-O Sym.	Crystal Sym.
La_2CuO_4[23]	1.32	1x10^{18}	24	38	40	tilted Octahe.	Tetra.
$SmOFeAs$ [21]	0.85	0.6x10^{18}	24	58	55	*tilted Pyram. (Fe-As)	Tetra.
$YBa_2Cu_3O_7$ [22]	1.16	2x10^{18}	12	92	92	distorted Pyram.	Ortho.
$Hg-1201$ [17][12]	0.95	1.2x10^{18}	13	96	98	Octahe.	Tetra.
$Hg-1212$ [17][12]	1.27	2.4x10^{18}	7	126	127	Pyram.	Tetra.
$Hg-1223$ [16][17][12]	1.58	3.1x10^{18}	5	135	134	Pyram.	Tetra.
$(Hg,Re)-1223$ [9]	1.56	3.2x10^{18}	5	134	133	Pyram.	Tetra.
$Hg-1234$ [18]	1.89	4.4x10^{18}	4.5	125	125	Pyram.	Tetra.
$Hg-1245$ [19]	2.21	5.5x10^{18}	4.5	108	108	Pyram.	Tetra.

Tetra is Tetragonal, Orth is Orthorhombic, Pyram means Pyramidal, and Octahe is Octahedral. The *(Fe-As)* is a new system (2008).

TABLE II: Intrinsic term pressure dependence evaluated by Casimir energy

Compound	$K_c(10^{-3}GPa^{-1})$	$\partial T_c^{exp}/\partial P$	$\partial T_c^i/\partial P$	$\frac{-5}{4}T_c\frac{1}{d}\frac{\partial d}{\partial P}$	$\frac{-3}{4}T_c\frac{1}{\alpha}\frac{\partial \alpha}{\partial P}$	$\frac{1}{\alpha}\frac{\partial \alpha}{\partial P}$ $(10^{-3}GPa^{-1})$
$Hg-1201$ [12]	5.8	1.7	1.7	0.7	1.0	-13.8
$Hg-1212$ [12]	6.0	1.7	1.7	0.9	0.8	-8.4
$Hg-1223$ [16][12]	5.6	1.7	1.7	0.9	0.8	-7.9
$(Hg,Re)-1223$[9]	5.6	1.9	1.9	0.8	1.1	-11.0
$Hg-1234$[18]	5.8	1.2	1.2	0.8	0.4	-4.3
$YBa_2Cu_3O_7$ [22]	4.2	0.9	0.9	0.3	0.6	-8.7
La_2CuO_4 [23]	1.6	2.3	2.3	0.1	2.2	-73